

Electric hybrid airship with unlimited flight time

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Abstract. This paper examines the possibility of using photoelectric energy conversion during creation of electric unmanned aerial vehicles of a hybrid type. These vehicles should operate at altitudes up to 22,000 m and have an unregulated flight time. The problems arising during creation of such devices are their instability and poor controllability. Also they possess a number of disadvantages typical for airships: large size and, as a consequence, high windage and dependence on weather conditions; low maneuverability and, as a consequence, the difficulty of landing. These negative aspects of all circular wings resulted in complete rejection of their development. However, the considered disadvantages show the feasibility of creating hybrid aircraft. Particular attention in this paper is given to disk-shaped vehicles. They have less windage, do not need to turn around when changing the direction of flight. The presence of solar panels in combination with modern control and navigation systems make it possible to create new unmanned aerial vehicles with unlimited flight time. The aircraft dimensions are calculated as a function of the lifted mass and other parameters. Recommendations on possible operation parameters of hybrid airship are given.

1 Introduction

Lighter-than-air aircrafts have been always caught attention [1–3]. Nowadays new materials, new power sources, more advanced solar panels, modern control and navigation systems are being created [4–9]. This contributes to the creation of new type of aircraft, in particular unmanned aerial vehicles with unlimited flight time [10–14]. The characteristic feature of airships is that they do not have a strictly defined limit on the mass of the transported cargo [15–18] in contrast to heavier-than-air aircrafts. The most significant advantages of airships are: higher reliability and safety in contrast to airplanes and helicopters; no strict limitations on carrying capacity; unlimited flight time; no need for runways.

However, it is necessary to itemize their disadvantages:

- Large dimensions and, as a consequence, high windage and dependence on weather conditions;
- Low maneuverability and, as a result, the difficulty of landing;
- Relatively low speed (up to 150 km/h);
- High cost of filler gas - helium or the danger of hydrogen;
- Aerostatic imbalance, which forces one to carry a large amount of ballast onboard, which reduces the payload.

The considered disadvantages show the feasibility of creating a hybrid aircraft. Thus the aim of this work is to consider physical and engineering bases for creation of a new type of aircraft with unlimited flight time.

2 Materials and methods

Here we consider a new type of hybrid aircraft, which is formed by combining an airship with a helicopter. Such construction will have smaller dimensions than an airship and will enable elimination the problem of aerostatic imbalance. This increases the carrying capacity and efficiency of the vehicle. The maneuverability of vehicle is greatly increased, and the difficulties with landing of vehicle are eliminated. The use of an electric propulsion system together with a solar battery allows the development of unmanned aerial vehicles that do not require landing (atmospheric satellites). Currently operating atmospheric satellites are airplanes that operate at altitudes of 19,000 - 22,000 m and are rather fragile structures. Hybrid aircraft based on various types of aerostats compare favorably with airplanes, since they have a more reliable design and can lift more weight. These aircraft are compatible with solar panels, which require large areas to obtain sufficient electrical power. The shape of the considered aerostat is shown in Figure 1.

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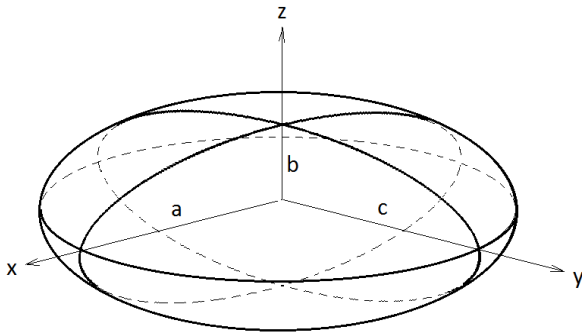


Fig. 1. Aerostat in the form of an ellipsoid of rotation.

It should be noted that the aerostat can be filled with a mixture of hydrogen and helium to provide greater lift, lower gas cost and, at the same time, operational safety. The presence of the aerostatic part changes the dynamics of the helicopter or multicopter flight, which requires the improvement of the control programs.

In the hovering mode, the thrust force of the propeller-driven groups (F_i) must balance the weight of the aircraft together with the aerostatic lift (Archimedes force F_a). From this condition, it is possible to determine the required rotational speed of the propellers and the engines power required to provide the hovering mode of vehicle.

The power of engines, in turn, determines the required capacity of the storage battery and its weight (Arzamatshev and Kryuchkov 2014). For devices of this type, the hovering mode is the most power-consuming.

Obviously, these aircrafts have their own special area of application, that require a long flight time (more than 24 hours) or a high flight altitude (20,000-2,000 m), that can't be achieved by aircrafts of other types. The use of two different physical principles for maintaining an aircraft in the air significantly reduces the risk of its falling. The presence of an additional energy source significantly expands the aircraft capabilities. An additional source of energy can be used not only to power the power plant, but also to power the payload equipment. The lower boundary of the flight level is determined by the safety of device operation and must be outside the flight zone of civil aviation (12,000 m) and above the clouds. So, the solar battery can be used as the main source of electricity.

The following equation is used to determine the aircraft dimensions from the condition of equality between the aircraft weight and the aerostatic lift at a given height:

$$\frac{4}{3} \pi \cdot \beta_1 \cdot (\rho_{\text{air}} - \rho_{\text{He}}) \cdot a^3 - (2 \cdot \rho_{\text{shell}} + \rho_{\text{sb}}) \cdot \pi \cdot k_1 \cdot a^2 - m_r - M_{\Sigma} = 0 \quad (1)$$

where

$$m_r = 2 \cdot \pi \cdot \mu_r \cdot n_r \cdot \sqrt{\frac{1 + \beta_1^2}{2}} \cdot a, \quad (2)$$

$$k_1 = 1 + \frac{\beta_1^2}{\sqrt{1 - \beta_1^2}} \cdot \ln \frac{1 + \sqrt{1 - \beta_1^2}}{\beta_1}; \quad (3)$$

β_1 is the ratio between the semiaxes of the ellipsoid upon condition $a=c > b$

$$\beta_1 = \frac{b}{a} = 0.25; \quad (4)$$

ρ_{air} and ρ_{He} are densities of air and helium at the considered height, respectively ($\rho_{\text{air}}=0.08533 \text{ kg/m}^3$, $\rho_{\text{He}}=0.0122 \text{ kg/m}^3$);

ρ_{shell} and ρ_{sb} are densities of the aerostat shell material and solar battery material, respectively ($\rho_{\text{shell}}=0.1 \text{ kg/m}^2$, $\rho_{\text{sb}}=0.3 \text{ kg/m}^2$);

μ_r is the specific mass of carboxyl reinforcing elements, kg/m ; n_r is the number of reinforcing elements ($\mu_r=0.08 \text{ kg/m}$, $n_r=6$);

M_{Σ} is the mass lifted by aerostat, which includes: mass of the traction electric motors (m_{mot}), mass of the control system (m_{cs}); mass of the accumulator battery (m_{ac}), mass of the payload (m_{pl}).

For flights at high altitudes from 12,000 to 22,000 m, hybrid aircraft must be large, which predetermines a more complex aerostat design and shape. Further we consider a simplified design of an aircraft to determine the energy parameters of its power plant. As a basic condition, we assume that the aircraft should not descend below the level of 20 km, i.e. the lifting aerostatic force must ensure that the vehicle hangs in the air in a de-energized state.

The excess pressure inside the aerostat shell is $\Delta P=2 \text{ kg/m}$, which is taken into account when determining the helium density. As a result, we obtain an equation equivalent to equation (1). The energy generated by solar batteries (SB) depends on its area S_{sb} , efficiency η_{sb} , time and season. If we assume that the surface area of solar battery covers half of the outer surface of the ellipsoid, then the average power generated by the solar battery is

$$P_{\text{sb}} = 1000 \cdot \eta_{\text{sb}} \cdot k_u \cdot k_1 \cdot \pi \cdot a^2, \quad (5)$$

where η_{sb} is the efficiency of SB at AM0, 25°C in the optimal point of the current-voltage characteristics, W/m^2 ; k_u is the utilization factor of solar radiation, which depends on the coordinates of the aircraft in space, time, season.

Preliminary studies show that the presence of four stabilizing electric motors (Figure 2), with the appropriate adjustment of regulators, allows one to eliminate oscillations of the device, and it stabilizes.

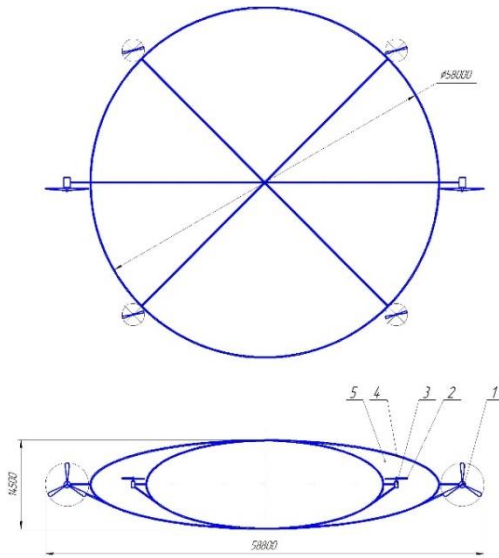


Fig. 2. Quadcopter-based hybrid aircraft (1 - traction motor; 2 - vertical thrust screw; 3 - stabilizing electric motor; 4 - frame; 5 - shell).

The flight was stable even when the speed reached 100 km/h. Energy costs become very high already at such speeds. Vertical control can bring the drone to a predetermined height without changing buoyancy, using the wing effect. In this case, the lift is carried out by the oncoming air flow, which acts on the vehicle like on a wing. The device can maintain a given altitude only by moving, but this will require additional energy, as for the flight of an aircraft. Therefore, the solar battery must provide enough power for the aircraft to function.

3 Results and discussion

The aerostat dimensions were calculated as a function of mass M_{Σ} , which the aerostat holds in the hovering mode at an altitude of 20,000 m. The calculation results are summarized in Table 1.

According to Table 1, the dimensions of aerostat can be selected depending on the mass of the payload. For definiteness, consider an airship as a cellular repeater in the region of Ryazan, Russia. The cellular communication unit has the following parameters: power

Table 1. Relationship between dimensions of the aerostatic part of the airship and the mass M_{Σ} , which is held by the aerostat in hovering mode at an altitude of 20,000 m.

Density of shell material $\rho_{shell}=0.1\text{ kg/m}^2$	Mass lifted by the aerostat M_{Σ} , kg	0	40	80	120	160	200	240	280	300	320	340
	Semimajor axis of ellipsoid a, m	24.4	25.2	25.9	26.6	27.2	27.7	28.2	28.7	28.9	29.2	29.4
Solar battery	Average power of the solar battery, kW	297	317	335	351	367	382	396	410	417	424	430
Note. Atmosphere parameters at a height of 20000 m: pressure 5468 Pa; temperature 216.5 °K; air density 0.08533 kg/m ³ . SB characteristics: $p_{SB}=200\text{ W/m}^2$; specific mass $\rho_{SB}=0.3\text{ kg/m}^2$												

Table 2. Energy indicators of cellular communication and airship control units.

Characteristic, its designation, meas. unit	Calculation formula	Calculation results
The cellular communication unit		
Estimated battery capacity, C, A·h	$C = \frac{P_{cc} \cdot t}{U \cdot K_p} \cdot k_z$	$C = \frac{300 \cdot 17}{24 \cdot 0.6} \cdot 1.2 = 425$
Output rated current from the battery, I, A	$I = \frac{P_{cc}}{U}$	$I = \frac{300}{24} = 12.5$
The total amount of energy stored by the battery, W, W·h	$W = U \cdot I \cdot t$	$W = 24 \cdot 12.5 \cdot 17 = 5100$
Weight of batteries for the cellular unit, m_{ac1} , kg	$m_{ac1} = \frac{W}{\mu}$	$m_{ac1} = \frac{5100}{200} = 25.5$
The airship control unit		
Estimated battery capacity, C, A·h	$C = \frac{P_{sp} \cdot t}{U \cdot K_p} \cdot k_z$	$C = \frac{320 \cdot 17}{24 \cdot 0.6} \cdot 1.2 = 453$
Output rated current from the battery, I, A	$I = \frac{P_{sp}}{U}$	$I = \frac{320}{24} = 13.3$
The total amount of energy stored by the battery, W, W·h	$W = U \cdot I \cdot t$	$W = 24 \cdot 13.3 \cdot 17 = 5440$
Weight of batteries for the cellular unit, m_{ac2} , kg	$m_{ac2} = \frac{W}{\mu}$	$m_{ac2} = \frac{5440}{200} = 27.2$
Weight of batteries for electric units, m_{Σ} , kg	$m_{\Sigma} = m_{ac1} + m_{ac2}$	$m_{\Sigma} = 25.5 + 27.2 = 52.7$
Note. Modern Li-ion batteries have the following weight and dimensions: $\mu=200\text{ W}\cdot\text{h/kg}$ and $v=250\text{ W}\cdot\text{h/l}$		

consumption $P_1=300$ W; mass $m_{el}=47$ kg; dimensions $520 \times 400 \times 260$ mm. The airship control unit has the similar parameters: $P_1=320$ W; mass $m_{el}=50$ kg; dimensions $530 \times 420 \times 270$ mm. The stabilization system includes four electric motors with a nominal power of $N_{mst}=1500$ W. Cellular communication equipment, airship control unit and stabilization system operate within 24 hours. During daylight hours, from 9 am to 3 pm, a solar battery works, which within 7 hours must ensure the batteries recharging and the vehicle operation at an altitude of 20,000 m. The backup time for electrical equipment is $t=17$ hours at a standard voltage $U=24$ V. Assume that the permissible level battery discharge is 60% ($K_{dc}=0.6$). The cellular communication unit and the airship control unit consume current of the same order, therefore, we consider these consumers separately. The obtained calculation results are summarized in Table 2.

The total mass of the cellular communication and control units for the airship with batteries is

$$M_{ucc} = m_{el1} + m_{el2} + m_{\Sigma} \quad (6)$$

$$M_{ucc} = 47 + 50 + 52.7 = 149 \text{ kg.}$$

The considered airship has a shape of an ellipsoid of rotation (Figure 2), and it predetermines the design of the power plant. It must have two traction electric motors with a direct drive of propellers, providing horizontal movement and four electric motors with propellers to ensure stable flight of the vehicle. The mass of these elements depends on the vehicle motion speed. For definiteness, we consider an airship with mass of $M_{\Sigma}=320$ kg (Table 1).

The resistance force of air is directed against the vehicle speed, its value is proportional to the typical area S , the medium density, and the squared speed V :

$$X_0 = C_{x0} \cdot \frac{\rho \cdot V^2}{2} \cdot S, \quad (7)$$

where C_{x0} is the dimensionless aerodynamic drag coefficient.

Table 3. Energy indicators of power plants providing motion and hovering of an airship.

Characteristic, its designation, meas. unit	Calculation formula	Calculation results
Traction electric motors		
Typical area S , m ² .	$S = \pi \cdot a^2 \cdot \beta$	$S = 3.14 \cdot 29^2 \cdot 0.25 = 660.2$
Power required to overcome the ambient medium, P_0 , W	$P_0 = C_{x0} \cdot \frac{\rho_c \cdot V^3}{2} \cdot S$	$P_0 = 0.1 \cdot \frac{0.085 \cdot 20^3}{2} \cdot 660.2 = 22533$
Power of traction motor N_{tm} , W	$N_{tm} = \frac{P_0}{2 \cdot \eta_{vt}}$	$N_{tm} = \frac{22533}{2 \cdot 0.8} = 14083$
The nearest standard power N_{st} , W	N_{st}	$N_{st}=15000$
Traction motor weight, m_{tm} , kg	$m_{tm} = \frac{N_{cm}}{\mu_0}$	$m_{tm} = \frac{15000}{1000} = 15 \text{ kg}$
Rated current consumed by the electric motor I_{rc} , A	$I_{rc} = \frac{N_{st}}{\eta \cdot U}$	$I_{rc} = \frac{15000}{0.8 \cdot 24} = 781 \text{ A}$
Stabilization system motors		
Power of stabilization system motor, N_{ssm} , W	N_{ssm}	1500
Mass of stabilization system motor m_{ssm} , kg	$m_{ssm} = \frac{N_{ssm}}{\mu_{ssm}}$	$m_{ssm} = \frac{1500}{1000} = 1.5$
Rated current consumed by the electric motor I_{rss} , A.	$I_{rss} = \frac{N_{ssm}}{U \cdot \eta}$	$I_{rss} = \frac{1500}{24 \cdot 0.8} = 78.1$
Calculated capacitance of accumulator battery, C_{cc} , A·h	$C_{cc} = \frac{n_{mot} \cdot N_{ssm} \cdot k_{load} \cdot t}{\eta P_{max}}$	$C_{cc} = \frac{4 \cdot 1500 \cdot 0.6 \cdot 17}{0.9 \cdot 24 \cdot 0.6} \cdot 1.2 = 4722$
The total amount of energy stored by the stabilization system batteries, W_{cc} , W·h	$W_{cc} = U \cdot (I \cdot k_{load}) \cdot t$	$W_{cc} = 24 \cdot (78.1 \cdot 0.6) \cdot 17 = 19119$
Mass of batteries for stabilization system, m_{cc} , kg	$m_{cc} = \frac{W_{cc}}{\mu}$	$m_{cc} = \frac{19119}{200} = 95$
Mass of batteries for main traction system, m_{tr} , kg	$m_{tr} = m_{\Sigma} - m_{cc} - 4m_{ssm} - 2m_{tm} - M_{ucc}$	$m_{tr} = 320 - 95 - 4 \cdot 1.5 - 2 \cdot 15 - 149 = 40$
Total energy stored by a battery for main traction system, W , W·h	$W = m_{tr} \cdot \mu$	$W = 40 \cdot 200 = 8000$
Reservation time for traction system operation, t , h	$t = \frac{W_{tr}}{U \cdot I}$	$t = \frac{8000}{24 \cdot 781} = 0.43$ (25 min)
Note. The stabilization system motors operate at maximum efficiency of $\eta_{max}=0.9$. The maximum efficiency is achieved with a load factor of $k_{load}=0.6$. The battery capacity safety factor is $k_{ep}=1.2$. The allowable battery discharge rate is $K_p=0.6$ (60%). The number of engines in the stabilization system is $n_{mot}=4$.		

The power required to overcome this component of the drag force is proportional to the cubed speed

$$P_0 = C_{x0} \cdot \frac{\rho \cdot V^3}{2} \cdot S, \quad (8)$$

The power and weight of the power plant were calculated under the condition that it will provide the aircraft with motion at a speed of $V=20$ m/s (72 km/h). The calculation results are summarized in Table 3.

4 Conclusion

1. An electric hybrid airship can be created using the existing element base, but its flight time is limited by the recharge cycle of Li-ion batteries and is approximately 5 years.

2. The safe operation of an aircraft is directly related to an accurate forecast of weather conditions in flight areas, which is typical for aviation in general and for airships in particular.

3. The electric power plant ensures the operation of the aircraft at altitudes up to 22,000 m. The maneuvering range largely depends on the efficiency of the solar battery and the specific capacity of the storage batteries.

4. The considered aircraft does not make it possible to use the traction power plant within 24 hours, which can function normally only during daylight hours. Therefore, it is important to predict the atmospheric conditions for the nearest night time, which allows one to move the vehicle to a safe place during daylight hours within 6-7 hours.

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